Plume-deployed Inflatable for Launch and Landing Abrasive Regolith Shielding (PILLARS)

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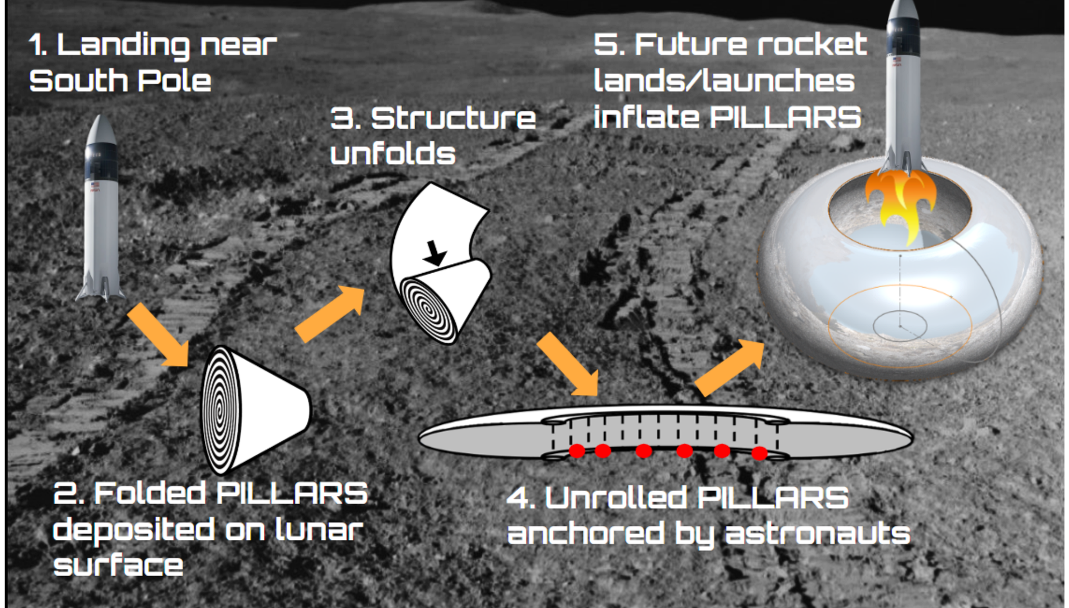
System Proposed & Technical Objectives:

- PILLARS is a **Low SWaP, inflatable** solution for **dust mitigation** and containment during **launch and landing**
- Provides a **novel, lightweight** berm that **protects lunar infrastructure** in a 15km radius around the landing pad
- Uses the **rocket plume to inflate** to **minimize** power consumption and system complexity
- **Easy to deploy** anchors for securing the structure
- **High strength and durable** inflatable structure to be used as a **long-term** landing infrastructure

System CONOPS



Team & Management Approach

Dr. Soon-Jo Chung, Faculty Advisor, Caltech
Mr. Kalind Carpenter, Faculty Advisor, JPL
Kevin Gauld, EE '24, Project Management Lead
Lily Coffin, ME '24, Systems Lead
James A. Scott III, ME '26, Deployment Lead
Isabella Kwaterski, ME '25, Materials Lead
Samuel Foxman, CS '26, Fluids Lead
Emily Xu, EE '27, Mission Concept Co-Lead
Hannah Ramsperger, ME '27, Mission Concept Co-Lead

25 Caltech undergraduate students majoring in:

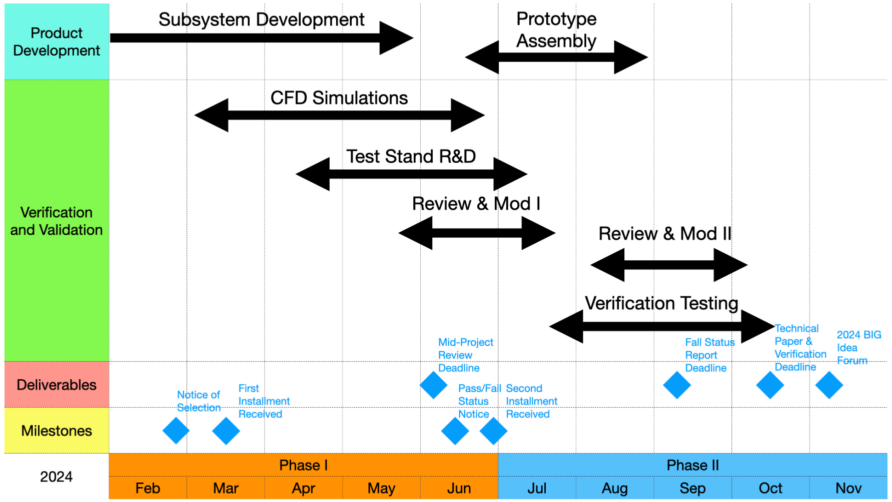
Computer Science	Electrical Eng.
Mechanical Eng.	Chemistry
Chemical Eng.	Physics
Applied Math	Math

Approach:

- Agile project management
- Caltech AIAA Student Branch Project

Project Schedule and Cost:

- Total proposed budget: **$150,000.00**
  - Phase 1 Total: **$75,000.00**; Phase 2 Total: **$75,000.00**



1 Summary Statement

The Artemis missions seek to establish a thriving lunar base and economy through a sustained human presence and supporting infrastructure. To enable this, powerful landers will deliver humans, infrastructure, and other critical components onto the lunar surface. Rocket landings and launches generate rocket plumes that kick up large quantities of lunar regolith and eject it across the surface. These destructive particles are small, sharp, and fast, posing a concern for all lunar assets which must survive the impact of these dust storms. As such, the mitigation of damage caused by regolith is necessary for the creation of permanent and sustainable lunar infrastructure.

We propose PILLARS: a Plume-deployed Inflatable for Launch and Landing Abrasive Regolith Shielding. PILLARS is a low-mass, low cost solution to mitigate the destructive effects of rocket plumes. When not in use, PILLARS is deflated to a nearly flat configuration. As a rocket launches or lands in the center of the system, the radially-symmetric plume exhaust inflates the bag to 20 meters tall, blocking and trapping the kicked up lunar regolith. PILLARS is a long term dust shielding solution to be used for many successive launches and landings. Since plume travels faster than dust, PILLARS will inflate a dust barrier long before dust is able to escape the area. As all displaced regolith remains in the area after the rocket has landed, the regolith resettles, enabling the site to be used for successive launches and landings. When the plume subsides the system passively deflates, allowing for astronauts and rovers to reach the rocket site quickly and easily.

In developing PILLARS, we considered many points of failure and engineering challenges in the design of such a berm. To withstand the impact of regolith, we selected Aluminized Kapton Kevlar fabric for its UV-resistance and high tensile strength. When interfacing with rocket plume, there is a heat concern, especially when using deformable and inflatable fabric. By placing PILLARS radially far from the rocket, we take advantage of isentropic expansion and radiative cooling, allowing the plume exhaust to cool down before interacting with the berm. Through extensive fluid modeling validated against vacuum testing, the geometry of PILLARS will be developed to optimize for dust mitigation while ensuring reusability of the system for many launches and landings. Material abrasion testing in high stress and high temperature environments will provide context for the longevity of our system and its failure conditions. We will aim to conduct a $\frac{1}{10}$ scale field demo to show the validity of our inflation mechanism. Through a testing campaign that combines simulations, lab testing, and field demonstrations, our system our system will be brought to a Technology Readiness Level (TRL) of 4, nearly 5. PILLARS has the potential to alleviate dust mitigation concerns for the Artemis mission, with low-mass inflatable technology making cost-effective shielding possible for early lunar base architectures.

2 Problem Statement and Background

2.1 Challenge Addressed

NASA's Artemis mission seeks to establish the infrastructure for a long-term lunar habitat and thriving lunar economy. In order to do so, it will require various heavy duty landers such as SpaceX's Starship or Blue Origin's Blue Moon lander to land payloads and astronauts on the surface of the Moon. In doing so, the rocket plumes generate dust ejecta which sends fine particles with jagged edges traveling incredibly fast [28, 16]. This causes the dust to effectively sandblast unprotected lunar infrastructure as seen with Surveyor III [12]. The concern with ejected lunar dust is so significant that the Lunar Surface Innovation Consortium (LSIC) has found that mitigation techniques are necessary to protect the future lunar outpost from the dust due to launch and landing [7]. Furthermore, LSIC analysis indicates that current proposed construction techniques for either mitigating the dust or enabling a distant landing site may need a much earlier maturation than currently anticipated to complement projected lunar activity. Although ISRU-built infrastructure is a long term goal for Artemis, there is a significant incentive for a low SWaP, intermediary system to mitigate this problem while Artemis validates and builds up its ISRU infrastructure and lunar base. As such, PILLARS seeks to fill this niche through the advantages of an inflatable system.

2.2 Mission Summary

Our solution to this destructive dust problem, PILLARS, is a 20m tall, 40m wide berm. The inflated structure will shield dust kicked up by rocket plumes on landing and launch, preventing it from reaching any nearby infrastructure. Most notably, the structure will inflate by the force of the rocket plume alone, allowing the structure to passively inflate and automatically deflate after touchdown to allow easy ingress for astronauts and transportation systems. This solution provides maximum mass and power savings, with a stow volume orders of magnitude smaller than deployed volume.

2.3 Mission Goals

Based on NASA's Moon to Mars Architecture Objectives [25] and Lunar Surface Innovation goals [23, 27], we have determined the following mission goals for our system.

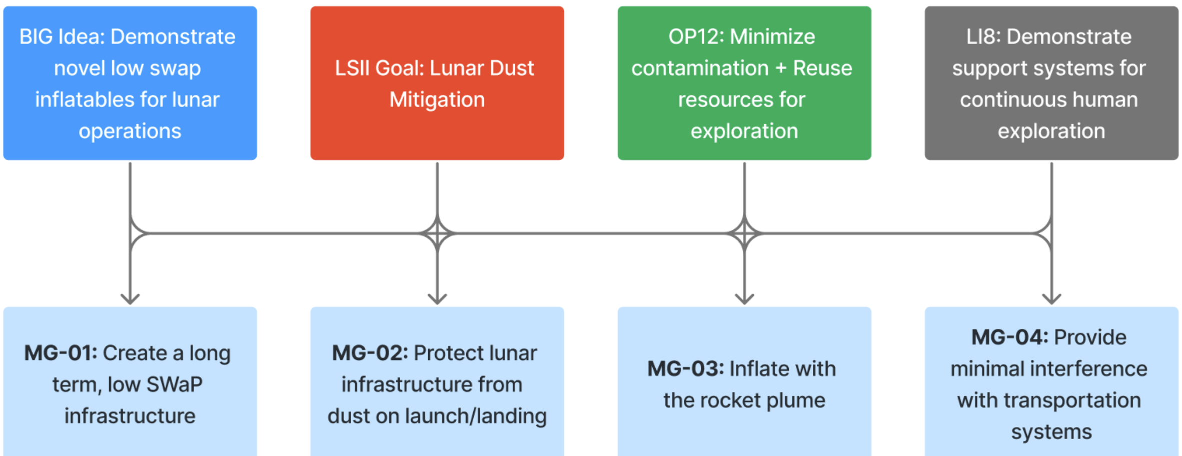
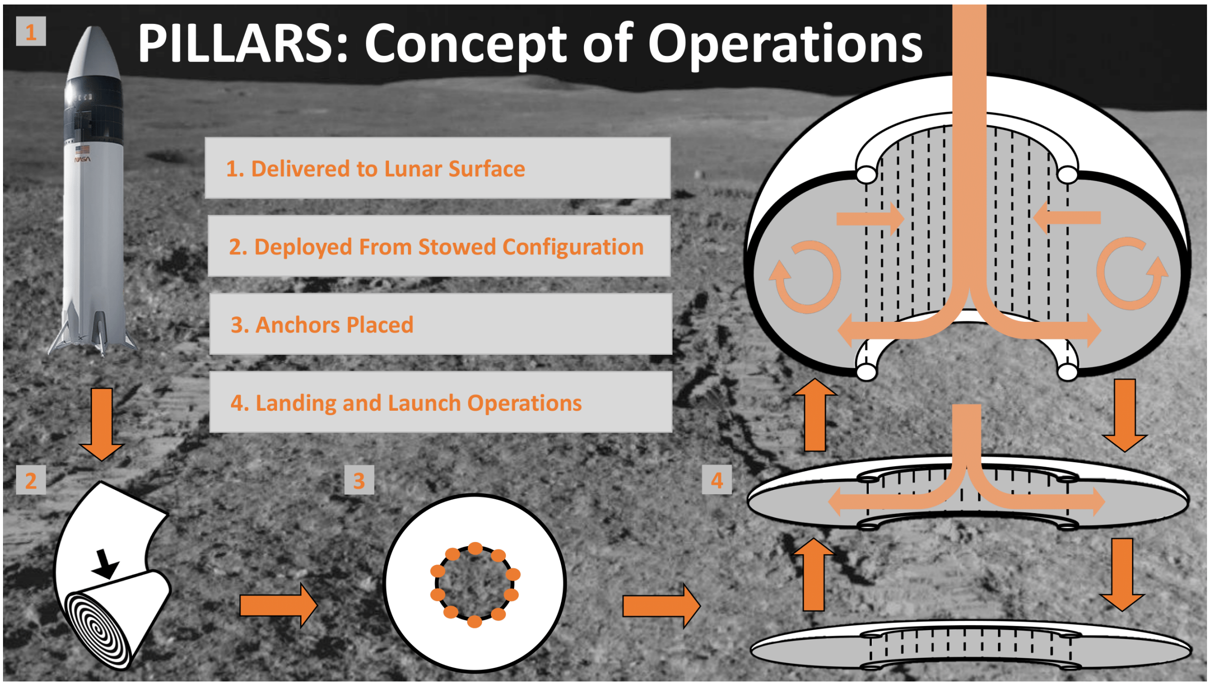


Figure 2-1

2.4 Mission Scenarios

The primary mission scenario for the usage of PILLARS is to protect the lunar base and infrastructure from landers during the early phases of Artemis while more complex surface and landing architecture is still being verified, developed, and scaled. This fills an important niche in launch and landing technologies as other proposed solutions [15, 35, 18] often trade between ambitious construction/surface preparation, complex modifications to landing architecture, short lifespan, and high maintenance. Furthermore, this system can be coupled with a landing pad or surface preparation technologies as a means to provide additional mitigation. Due to the critical nature of landing large payloads for Artemis, PILLARS is essential for exploration and commercial operations on the Moon.

2.5 System ConOps



2.6 TRL Advancement

System	Cur. TRL	Advancement Plan	End TRL
Inflatable Material	3	MT-01, MT-02, MT-03	5
Mesh for plume dissipation	4	CFD-02, MT-01, MT-02, MT-04	5
Rocket Inflation	2-3	MT-01, MT-02, MT-03, MT-04, CFD-04, CFDV-03	5
Anchoring system	4	MT-05, MT-06, FT-03	5
Radio Beacon Landing	5	N/A	5
Berm for dust mitigation	3	CFD-03, LT-01, LT-02, LT-04, FT-03	4-5
CFD analysis for berms and lunar dust	3	CFD-01, CFD-02, CFD-03, CFD-4, CFDV-01, CFDV-02, CFDV-03	5
Inflatable deployment	3	FT-01	4-5
Deflation of system	3	FT-02, FT-03	4-5

Figure 2-2: This table maps critical subsystems and shows how the testing plan advances the TRL.

3 Project Description

3.1 System Requirements & Design Assumptions & Risks

ID	Design Assumption	Justification
DA-1	The system is used during early artemis during low power, ISRU, and construction capabilities	This system is most valuable during Early stage Artemis when multiple large landers are needed to setup more complex
DA-2	Full system deployed on Starship	Starship will be necessary for establishment of infrastructure. We can use its high payload capacity
DA-3	High payload surface transport available	To transport PILLARS from the lander to a landing site, high payload transportation such as ATHLETE robots must be used
DA-4	100m radius landing site that is flat (slope < 5°)	Uneven terrain is out of lander and inflatable scope. (LSIC 2020)
DA-5	Radio beacons decrease landing margin to 3 m	Radio beacons to improve landing accuracy have been proposed/ tested. Landing beacons and lack of atmosphere should allow
DA-6	Support from astronauts to deploy infrastructure	Astronauts will be present to facilitate non-trivial deployment processes
DA-7	Low orbital activity	Some ejected regolith dust becomes orbital, but likely there will not be enough orbital activity in which this becomes a concern

ID	L1 Requirement	Justification	Mission Goal
1.1	PILLARS shall contain >90% lunar dust ejected in a 20 km radius and protect all structures under 20m	Expected lunar infrastructure to be contained within 20km. Tallest structure to be 20m solar array (Astrobotic)	MG-02
1.2	PILLARS shall be capable of utilizing the rocket plume for inflation	Mission goal, provides more optimal inflation method	MG-03
1.3	PILLARS shall not present any hazards to astronauts and payloads transported out of a landed vehicle	The lander needs to be easily accessible for astronauts and transportation systems	MG-04
1.4	PILLARS shall require minimal servicing and setup	Minimize workload on astronauts	MG-01; MG-04
1.5	PILLARS shall survive the forces and abrasion of 15 launches/landings	See section 3.9 for estimation	MG-01; MG-02
1.6	PILLARS shall have a functional lifespan of > 3 yrs	See section 3.9 for estimation	MG-01
1.7	PILLARS shall be low SWaP	Capitalize on inflatable tech	MG-01

ID	Inflatable Requirements	Justification / ID
2.1	The PILLARS Inflatable shall occupy less than 10% of the volume and less than 10% of the mass of the Starship lander payload capacity	This allows the system to be Low SWaP (1.7)
2.2	The PILLARS Inflatable shall inflate to contain dust that has a trajectory into the 20km protected zone	1.1
2.3	The PILLARS Inflatable shall resist the pressure and temperature of rocket plume for 15 launches	1.5
2.4	The PILLARS Inflatable shall survive the high-speed displaced dust for 15 launches	1.5
2.5	The PILLARS Inflatable shall survive in the lunar environment for 3 years	1.6
2.6	The PILLARS Inflatable shall provide a TBC m of landing error margin	1.3
2.7	The PILLARS Inflatable shall operate with minimal intervention for 15 launches	1.4
2.8	The PILLARS Inflatable shall be easily deployable	1.2, 1.4
2.9	The PILLARS Inflatable shall deflate to a configuration that does not interfere with transportation and astronaut activity	1.3

ID	Mesh Requirements	Justification / ID
3.1	The PILLARS mesh shield shall have TBC Yield strength to be able to withstand high speed regolith impact	1.5
3.2	The PILLARS mesh shield shall be impervious to UV radiation	1.6
3.3	The PILLARS mesh shield shall be able to withstand temperature fluctuation from ~100K - 575K	1.6
3.4	The PILLARS mesh shall be porous enough to permit gas flow, slow down 10-70μm regolith dust, and block abrasive 1-2mm glass shards	1.5
3.5	The PILLARS mesh shield shall not adhere to regolith dust	1.5

ID	Anchor Requirements	Justification / ID
4.1	Anchors shall react TBC lift and TBC MN shear force	1.5
4.2	Anchors shall embed in the regolith to react the plume forces	1.4 (no advanced setup)
4.3	Anchors shall be easily deployable	1.4
4.4	Anchor deployment shall require < TBC W of power	1.4, 1.7
4.5	Anchors shall keep the deflated PILLARS configuration open to capturing the plume for the next launch/landing	1.2, 1.4

Figure 3-3: These tables cover the key design assumptions, level 1 requirements, and subsystem requirements. Citations for DA-1 [24], DA-2 [25], DA-3 [9], DA-4 [22], DA-5 [21, 37, 30], DA-6 [24], DA-7 [12], 1.1 [3]

3.2 Inflatable Design Overview

Our focus in development is delivering a system architecture optimized for low SWaP and effective regolith shielding. This is driven by inflatable technology and rocket exhaust inflation that allow the deployment of a large inflatable with less compressed air mass and energy, increased resilience to damage, and passive deflation to allow easy ingress to the rocket. Initial feasibility analysis has been done but final geometries and requirements will be driven computational fluid dynamics (CFD) analysis of plume ejecta to explore the trade between desirable conditions and mitigation effectiveness.

3.3 System Deployment

3.3.1 Phase 1: Preliminary Deployment

PILLARS will undergo initial deployment on the Moon within a flat area, with a potential location identified as the peak near Shackleton Crater. With an average inclination of 3°, it is extremely suitable for Starship to land and deploy PILLARS safely. The deployment mechanism involves the manual inflation of two tori attached to the top and bottom of PILLARS. Astronauts do not have to erect any rigid structures, as they might for other dust-mitigation systems. There is much less astronaut time needed for the continued operation of PILLARS since the system will expand and deflate on its own after initial setup.

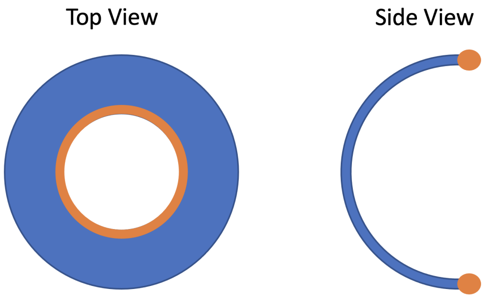


Figure 3-4: Top and side views for the inflatable torus structure. The blue areas represent the thin Kevlar outer shell of the inflatable, and the orange areas represent the two independently inflatable tori structures. The inflation of these two structures unrolls the structure from its stowed configuration.

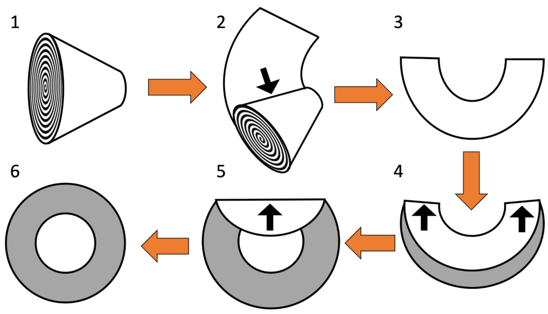


Figure 3-5: This shows the structure in all of its intermediate configurations from stowed volume to deployed volume.

3.3.2 Phase 2: Landing & Launching Inflation

During rocket launch and landing, PILLARS will passively inflate to a height of 20 meters. As PILLARS inflates, the mesh is elevated to shield the outer inflatable layer of PILLARS from sharp, hot regolith projectiles generated by the plume. Once the plume subsides, PILLARS will deflate passively. The uniform distribution of forces should allow the structure to inflate and deflate parallel to the launch axis. This is to be confirmed in field testing. Guided by the mesh layer, the anchors will catch the top of PILLARS while it deflates, creating an opening sufficient for plume entry.

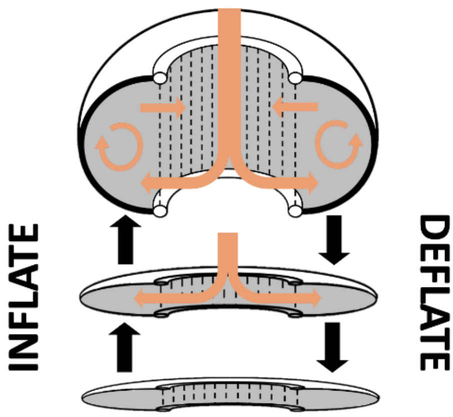


Figure 3-6: Plume-deployed inflation and deflation mechanism.

3.3.3 Deployed-Stowed Ratio and Mass

For the shape of PILLARS, we have chosen a torus. A torus has two radii, an inner which corresponds to the radius of the circle being revolved around the center point, and an outer which corresponds to the distance between the centerpoint and the center of the revolved circle. A horn torus occurs when the inner and outer radii are equivalent. For our design, we have essentially cut out a portion of the surface area at the center of the top and bottom of the torus equivalent to a circle with a radius equal to the radius of the torus, creating space for landings and launches. Tori have high volume-to-surface-area ratios, meaning that they can enclose a large volume while minimizing surface area. This means that PILLARS can deploy to a significantly large volume while requiring relatively minimal material. Furthermore, the torus shape provides PILLARS with inherent structural stability. The circular cross-section evenly distributes forces, making it resistant to deformation. This circular cross-sectional area is also where pressure is evenly distributed in a torus, helping it to maintain uniform inflation and pressure within the structure, reducing stress concentrations and enhancing overall stability.

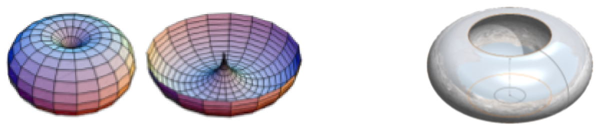


Figure 3-7: Horn Torus[10] (left) and PILLARS Design (right)

The deployed volume of our inflatable is the volume of the outer half of the torus. Applying Pappus's second centroid theorem for volumes, we can determine the expression for this volume.

$$V_{deployed} = V_{torus,outer} = 2\pi(r + \frac{4R}{3\pi})\frac{\pi R^2}{2}$$

$$\text{With } R = r = 10m : V_{torus,outer} = 1.406 * 10^4 \text{ m}^3$$

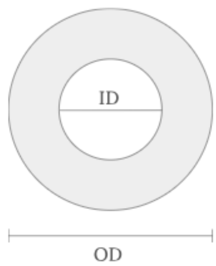
$$S_{torus,outer} = 2\pi(r + \frac{2R}{\pi})2R = 3.23 * 10^3 \text{ m}^2$$

Taking into account the inflatable and mesh layers, and deployment tori, the total stowed volume is 1.757 m^3. To find the deployed-stowed volume ratio, we take $V_{deployed}/V_{stowed}$ and get a ratio of 8001:1.

We can estimate the mass of the system given the volume of the layers and their respective densities. We will also include the mass of the maximum number of anchors potentially required for deployment, as well as structural elements discussed in future sections. Summing the masses of these components, we calculate the system mass to be about $2.8 * 10^3$ kg. As more inflatable and mesh layers are added, the system mass would increase by roughly $2.0 * 10^3$ kg per inflatable layer and mesh layer added. Through future testing and modeling, we will verify the exact quantity of layers needed for PILLARS.

Parameter	Predicted Range
Inner Diameter	20 - 40m
Outer Diameter	40 - 80m
Height	20 - 40m
System Mass	3,000 - 10,000 kg
Deployed Volume	20,000 - 112,000 m^3
Stowed Volume	2 - 8 m^3

(a) Parameter table



(b) Top-down view of PILLARS.

Figure 3-8: Design parameter values. Final values will be determined after Computational Fluid Dynamics simulations and physical validation.

3.4 Air Pressure and Temperature Considerations

The harsh conditions imposed by the rocket plume must be addressed. The plume gasses are at extremely high temperatures and pressures which puts constraints on the design of the inflatable. Thus, it is vital to know what pressures and temperatures the inflatable structure will be interacting with. Preliminary computational fluid dynamics (CFD) simulations estimate flows with speeds of about 3km/s before impact with shield, and pressures at the shield of $100kPa$, and temperatures of about $1000K$. The shield must be able to withstand these gas properties with a high safety margin.

The air pressure at the shield is 200 times the intermediate pressure due to stagnation [19].

Determining the stagnation pressure analytically is very difficult, if not impossible. At the distance of the shield, the mean free path length of each gas molecule becomes so large, on the order of 1m, such that the collection of molecules no longer behaves like a gas [39]. We can no longer assume continuum flow mechanics, instead we must model gas molecules individually.

We calculated the static pressure and temperature assuming continuum mechanics and isentropic flow, which yields pressures ranging from $2kPa$ to $40kPa$ depending on the assumptions of the flow field. With even more conservative estimates the isentropic calculations approach 6 MPa, which is 20% of the combustion chamber pressure, matching prior analytic calculations [20]. The uncertainty of these analytic estimates illustrate the need for computational fluid dynamics (CFD) which can simulate the rocket plume and provide much more accurate estimates.

We contacted Dr. Doug Fontes of Westmont College who ran preliminary CFD simulations of a rocket plume on the lunar surface [8]. These CFD simulations use direct-simulation Monte Carlo, a method which models the paths of individual molecules and is suitable for rarefied flows. CFD simulations estimate a stagnation air pressure of $100kPa$ at the distance of the PILLARS shield. This upper limit of the maximum pressure is comfortably below the yield strength of 1mm Kevlar.

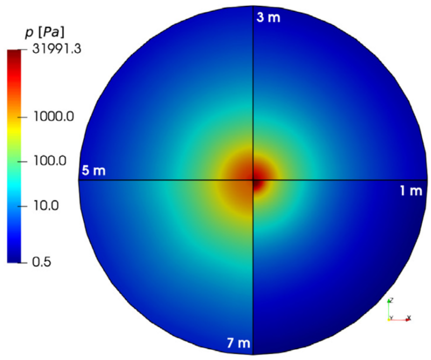


Figure 3-9: Static pressure on the lunar surface below a 40-ton lunar lander.

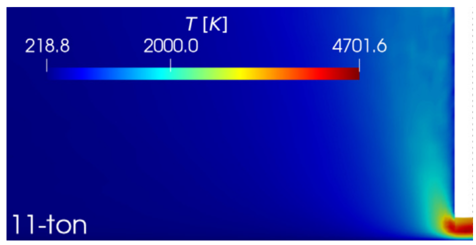


Figure 3-10: Temperature profile of an 11-ton lunar lander 1m above ground.

Note that these are rough estimates and further Computational Fluid Dynamics simulations are needed to produce more accurate estimations of what pressures and temperatures the shield needs to endure. The utilization of CFD to assist in the development of PILLARS is discussed in 3.10.1.

3.5 Inflatable Material Choice

The material choice for PILLARS considers the various environmental and technical challenges. The material needs to withstand the ambient lunar temperature range and radiation environment, high plume temperature and velocity, and high-velocity impacts of sharp regolith and micrometeoroids. It must also be lightweight to maintain the low-SWaP nature of PILLARS. As such, Kevlar presented itself as a strong candidate for our inflatable material, as Kevlar is high-strength and lightweight. However, Kevlar degrades rapidly in the presence of UV radiation. Given that the lunar environment has radiation peaks two hundred times that of Earth [11], the Kevlar we chose has laminate layers that prevent radiation from reaching it. Thus, the material we chose is Aluminized Kapton Kevlar, which is Kevlar sandwiched between layers of aluminized Kapton, bolstering it against both radiation and high temperatures.

	Tensile Modulus [GPa]	Tensile Strength [GPa]	UV Resistance	Thermal Resistance	Coefficient of Thermal Expansion [10-6/K]	Density [g/cm3]
Kevlar 29	70.5	3.6	Poor	Great	-3.96	1.44
Kevlar 49	112.4	3.6	Poor	Great	-4.86	1.44
Aluminized Kapton Kevlar	112.4	3.6	Excellent	Great	-4.86	1.44
Vectran	103	3.2	Poor	Good	-4.89	1.44
Nomex	3.4	0.34	Poor	Good	-2	1.38

Figure 3-11: Tradestudy of potential inflatable materials.

3.5.1 Sealing Layers

The seal of our inflatable layers must be able to withstand the high temperatures that our inflatable may potentially be exposed to. In these high-temperature conditions, traditional epoxies and adhesives may fail [2], and so stitching layers together with PTFE-coated Kevlar thread presents itself as the best option. The best stitch pattern can be determined through testing.

3.6 Mesh Layer

Significant amounts of high-speed regolith and larger projectiles pose a risk to PILLARS. We propose a porous yet robust mesh layer that blocks larger projectiles and a portion of ejected regolith, while allowing gas to bypass and inflate PILLARS. The material needs to be UV-resistant, high-strength, able to operate in high temperatures, porous enough to permit gas flow, and non-adhesive to prevent regolith from adhering to it and blocking the pores. Thus, the material we chose is PTFE-coated Kevlar, with an aperture size of 1.5mm, and a 1mm thickness. Kevlar is high-strength and lightweight, while PTFE is UV-resistant and has low adhesion. The material can reliably operate in temperatures ranging from 200K to 575K while maintaining its high strength and flexibility.

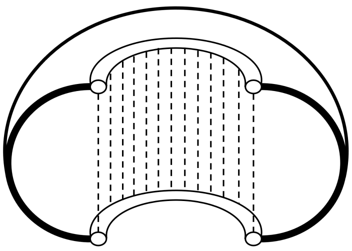


Figure 3-12: Cross section view of PILLARS with mesh as dotted lines.

Through testing, we will assess if the outer inflatable layer provides sufficient abrasion resistance on its own. Additionally, we will assess if it can operate reliably in the temperature range. Depending on testing results, we can conclude to forgo the mesh layer or if keeping it is essential. If keeping layer, testing will determine how many layers are needed.

Another use of the mesh layer is to anchor the top ring of the PILLARS outer layer to the bottom ring, which means that the seam between the mesh layer and the inflatable needs to withstand a significant amount of stress. The UV-resistant Kevlar thread should be strong enough to withstand this, but further testing will show what stitching patterns would be able to withstand the stress.

3.7 Anchoring

According to current plume analysis, the berm will encounter shear loads of approximately 82kN/m^2 if a landing or launching rocket is 3m off from the centerline. The maximum load on the anchors cannot be determined before CFD model development and verification, so we are considering the worst case scenario. If CFD shows that the order of this poor estimate is correct, there are some mitigations for force on inflatable we have considered. The inner radius of the structure can be increased to allow for more entropy loss before the plume encounters the structure. The radius is limited by the stow volume and mass, which we have far from maximized. At a potential reduction of dust mitigation efficiency, we could implement holes or flaps around the outer shell to allow some pressure venting. As a last resort, we can change the requirement for landing to stipulate higher landing accuracy.

3.7.1 Anchoring Analysis

To bolster the low-SWaP nature of PILLARS while also ensuring its structural integrity, we are considering materials such as titanium for anchoring due to its low-mass to high-strength character. We have determined that a 1.7 m titanium helical anchor planted 1.5 m into the ground can withstand 9 kN of shear load in lunar regolith [5]. Additionally, a titanium stake with a 4 cm shaft diameter could support approximately 32 kN [1] while other high strength Earth-based anchors such as the Manta Ray Anchor can go up to 89 kN (lowerbound due to increased coefficient of friction of lunar particles [4]) of load [17]. As the shear force on the anchors is to be determined through further simulations and can vary up to 1600 kN, the strength and number of stakes may vary between 2 kN to 89kN of supported shear load per stake and 10 to 20 anchors. We expect to utilize a combination of analysis and testing to determine and verify the optimal anchoring configuration.

Furthermore, if awarded funding, we plan on validating the precise details of our ideal stake geometry and dimensions through LPile—a software utilized on LATTICE for Caltech's 2022 BIG Idea Challenge [4]-–and finite element analysis using ANSYS student licenses.

3.7.2 Stake Driving Mechanism

Various rotary percussive drills have been used for driving stakes into the required depth. The Lunar missions and Apollo missions demonstrated the ability of rotary percussive drills to penetrate the lunar surface up to 1.6m [38]. More recently, Honeybee Robotics has developed the TRIDENT drill for low mass (20kg) and power (87 Watts) drilling into the lunar surface [40]. We will build off of the flight heritage of rotary percussive drills to provide a reliable and low power means for either robotic or astronaut-based deployment of the anchoring system into the required depths of the lunar regolith.

3.7.3 Stake-Inflatable Interface

At the high shear forces the inflatable will impart on the stakes, the inflatable material would be susceptible to failure around the anchors. To reinforce the interface between the stake and the inflatable, steel ring grommets will be used to protect the material from shear forces. The size of these rings will be driven by CFD and the determined maximum force on the inflatable. To prevent the inflatable from being pulled upward over the stake, the stake will be flanged so that the diameter of the top is greater than the hole size of the inflatable.

3.8 Manufacturing and Fabrication

Manufacturing of a PILLARS prototype will take place at the Jim Hall Design and Prototyping Laboratory, the GALCIT Machine Shop, and the Caltech Air and Outer Space Lab Space. Manufacturing and fabrication will include the dimensioning, sealing, and stitching of our inflatable layers, mesh layers, and structural tori.

3.9 Lifetime Analysis

3.9.1 Return on Investment Lifetime Estimation

We will spec the system lifetime needed as damage prevented to offset the overall cost of PILLARS. Estimating lunar solar power to be >\$100W and ISRU Water Ice activity to require 2.8 MW of power [29], the price for solar to sustain early ISRU mining can be lower bounded by $2.8MW * \frac{\$100}{W} = \$280M$. The upper bound of the cost of PILLARS is \$100M, which means we need to prevent at least a $\frac{\$100M}{\$280M} =$ 36% loss in power due to lunar abrasion. Using Surveyor III [12] data provides a conservative estimate of abrasion damage:

$$\pi \cdot (100\mu\text{m})^2/\text{pit} * 103\text{pit/cm}^2 \approx 3\%$$

of damaged surface area. We can use this as a rough estimate for the unusable surface area of solar panels and therefore power lost per landing. Assuming the damage compounds per landing we need to operate for about 15 launches and landings to prevent a projected 36% loss of solar power.

Since other elements such as habitation systems, surface mobility systems, radiators, and sensitive equipment being protected, this analysis quantifies a lower bound for the monetary value of the system. Thus, the overall return on investment will be significantly greater when the protection of additional expensive, mission-critical systems is considered.

Due to unclear projected launch cadence, we will use the estimated time to develop permanent landing infrastructure as a crude upper bound for the lifetime of the system in years. Given a construction time for an ISRU-based launch/landing pad of around 270 days [18] and implementing a generous safety factor of 4 to account for delays in verifying and scaling construction technology, we can upper bound the time to construct a landing pad to around 3 years to be an adequate intermediary for the growth of lunar infrastructure. Given the resilience of our materials to space conditions, this lifetime is feasible with modifications and further analysis.

3.9.2 Lunar Dust Buildup

During the Apollo landing, dust sheets containing anywhere from 10^8 to 10^{13} dust particles per cubic meter were kicked up according to photogrammetry estimates [13]. Given that Starship HLS has engines with 1000 times greater thrust than the lunar module [31], [36], we can roughly estimate that Artemis landings will kick up, on the high end, 10^{16} particles per cubic meter which may cause significant regolith buildup inside of the inflatable and drive the amount of servicing or overall system lifetime.

However, after a discussion with Dr. van Susante, who has contributed to significant plume surface interaction analysis [32, 14, 33], it is hypothesized that due to the speed of the particles, most particles that collide with PILLARS' Mesh layer will be deflected rather than captured. Thus, it is believed that the regolith build up inside the inflatable will be negligible and minimal servicing of the inflatable structure will be required.

3.9.3 Cratering on the Launch Pad

One lifetime concern is the usability of the landing site after the large displacement of regolith from prior rocket launches. With multiple launches and landings, an unprepared surface may become unusable due to change in its topography. Many companies such as Cislune are already funded to develop surface preparation robots, so this concern has been deemed out of the scope of PILLARS. However, basic surface preparation robotics is projected to be relatively low cost and power, and would work well with PILLARS.

3.10 Verification Through Testing and Demonstration

3.10.1 Computational Fluid Dynamics Simulations

Much of the system parameters, design, and testing will be informed by Computational Fluid Dynamics (CFD) modeling. Through the use of CFD, we can significantly reduce the uncertainty of our system and inform the design and testing that will follow.

1. Barebones temperature and pressure (CFD-01): Model the plume pressure and temperature from a Starship lander at 1 meter height. This is a first iteration of the model which will assume steady state and a fully-deployed rigid inflatable.
2. Plume pressure and temperature (CFD-02): Run many more cases with different rocket heights, shield radii, and deployment states. With laboratory validation, this will drive the requirements for the materials and systems to ensure survivability.
3. Plume, surface, and inflatable interaction (CFD-03): After the flow field is resolved, dust dynamics will be implemented into the model. We will insert spherical particles into the flow and integrate the drag force to determine the dust cloud. This will allow us to finalize the geometry that maximizes dust containment in addition to determining the abrasion that the system needs to survive.
4. Inflation simulation (CFD-04): Once the model is of sufficient maturity to predict plume and dust dynamics, we will simulate of the inflation dynamics of launch and landing. This will include the inner PTFE coated mesh layer which should help reduce the maximum temperature and pressure experienced by the outer shell.

Our CFD models will use direct simulation Monte Carlo (DSMC) in order to correctly model continuum and rarefied flow mechanics. We cannot use Navier-Stokes solvers because of the very low density in parts of our system. We will use OpenFOAM dsmcFoam solver, a free and open-source fluid modeling software that has been successfully applied to lunar dust plume modeling previously [8]. We expect modeling to take about 7 days per case on a 32-core machine, based on expert experience of Dr. Doug Fontes. We anticipate that we will run up to 100 CFD cases where we vary the height of the rocket, exhaust gas properties, PILLARS shield radius, and shield deployment state.

3.10.2 Lab Testing

CFD Validation Tests CFD models can be highly contentious without laboratory verification. To ensure that the models we are building to inform design requirements are accurate, significant model validation will need to progress in tandem with the development of our simulations.

1. Cold gas simulated plume pressure testing (CFDV-01): 1/200 scale testing in vacuum with a cold gas nozzle and rigid walls to validate the plume pressure as a function of radius. This will validate CFD-02
2. Scaled down dirty vacuum testing (CFDV-02): We will use a dirty vacuum chamber with a cold gas nozzle to do a 1/200 scale test of the dust containment. This will validate CFD-03.
3. Vacuum scaled down inflation testing (CFDV-03): We will inflate a 1/200 scale model in vacuum to simulate plume inflation in vacuum.

Materials Tests In order to verify the various components of our system, significant lab testing is required in order to advance our system to its necessary TRL. Our system will be validated in the lab with the following tests:

1. Abrasion/accelerated lifetime testing with regolith simulant (MT-01): Samples of aluminized Kapton Kevlar and PTFE coated Kevlar mesh will be sandblasted with the CAOS lab's existing lunar regolith clean box to be a control for further abrasion testing. Data will be collected utilizing X-Ray Computed Tomography machines at VJ Technologies. These machines will produce a scan at microscale, allowing us to view degradation within and on the surface of the material.
2. Abrasion/accelerated lifetime testing under stress (MT-02): The same protocol of data collection will be followed as in MT-01 but with materials in high tension.
3. Abrasion/accelerated lifetime testing under stress and high temperature (MT-03): Data will be collected according to the same protocol as MT-01 and MT-02 but under high tension and temperature.
4. Material stitch sealing/accelerated lifetime test (MT-04): We will test various stitch patterns of the kevlar sheets under the same conditions as MT-03 to determine best manufacturing processes.
5. Anchor Regolith Testing (MT-05): We will test anchoring mechanisms into lunar regolith simulant to verify that the anchors are capable of withstanding the projected loads on the system.
6. Anchor and Inflatable Interface load test (MT-06): We will test that the interface between the anchor and inflatable material is capable of withstanding the projected loads on the system.

3.10.3 Field Tests

A critical feature of the PILLARS system is the large size that the system inflates to. In order to have a better understanding of the system's dynamics at a larger scale, various field tests with a cheaper, non-flight ready kevlar, will be conducted:

1. 1/10 scale deployment test (FT-01): Will need to account for earth gravity and atmosphere but we will validate the deployment (from stowed) configuration mechanism of our inflatable system in the field.
2. Scale risk assessment for astronauts (FT-02): Assess uninflated configuration hazard for astronauts and rovers. The uninflated configuration will be analyzed and compared to requirements and capabilities of astronauts and surface mobility systems.
3. Scaled down hotfire testing (FT-03): Partnering with Cislune to use a scaled model rocket engine in a Mojave testbed. Note that due to budget and time limitations, an unsuccessful test will be inconclusive.

3.10.4 Test Traceability

Test ID	Success Criteria	Performance	Related
CFD-01	Analysis shows a suitable geometry wrt temperature and pressure for PILLARS exists	Operation	1.2, 1.5, 2.3
CFD-02	Analysis agrees with CFD-01	Operation	1.2, 1.5, 2.3
CFD-03	Analysis agrees with CFD-02 and shows a suitable geometry for dust containment	Operation, dust mitigation	1.1, 2.2, 2.6
CFD-04	Analysis agrees with CFD-02,CFD-03. Verifies inflation dynamics.	Operation	1.2, 1.4, 2.3
CFDV-01	Agrees with CFD-02.	Operation	1.2, 1.5, 2.3
CFDV-02	Agrees with CFD-03. Scaled prototype mitigates dust	Operation, dust mitigation	1.1, 2.2
CFDV-03	Scaled prototype inflates	Operation	1.2, 1.4, 2.3
MT-01	Acceptable abrasion damage observed. Survives 3 times operational lifetime.	Operation, Lifetime	1.5, 2.4, 3.1, 3.4, 3.5
MT-02	Acceptable abrasion damage observed. Survives 3 times operational lifetime.	Operation, Lifetime	1.5, 2.4, 3.1, 3.4, 3.5
MT-03	Acceptable abrasion damage observed. Survives 3 times operational lifetime.	Operation, Lifetime	1.5, 2.4, 3.1, 3.4, 3.5
MT-04	Acceptable abrasion damage observed. Survives 3 times operational lifetime.	Operation, Lifetime	1.5, 2.4, 3.1, 3.4, 3.5
MT-05	Anchor holds under maximum expected load and setup requires minimal power consumption.	Operation	4.1, 4.2, 4.3, 4.4
MT-06	Anchor inflatable interface holds under maximum expected load	Operation	4.1
FT-01	Scaled prototype deploys from stowed to unstowed configurations	Operation	1.4, 1.7, 2.8
FT-02	Scaled prototype poses minimal risk to astronauts and rovers.	Operation	1.3, 2.9
FT-03	Successful setup, plume inflation, dust mitigation, and deflation.	Operation	1.1, 1.2, 1.3, 1.4, 2.2, 2.3, 2.4, 2.7, 2.9, 4.1, 4.3, 4.4, 4.5

Figure 3-13: This table maps the various tests to success criteria, performance parameters, and related requirement IDs.

3.10.5 Testing Safety Plan

This section outlines safety plans for specific aspects of PILLARS development. Failure modes and risks will be thoroughly analyzed and mitigated before testing. In case of a medical emergency, Caltech Security will be notified.

Hot Fire Test Bed Hot fire field testing involves model rockets, developed in collaboration with Cislune for use in the Mojave desert, a few hours' drive from Caltech. Collaboration with Caltech Environmental Health and Safety (EHS) and Bureau of Land Management (BLM) ensures necessary training and permissions. The test stand, constructed with a large safety factor, will employ a remote launch controller and long-distance observation to ensure safety. Additional safety guidelines from the National Association of Rocketry will inform our plan on detonation-safe practices. Fire prevention and containment are prioritized, with readily available extinguishers, blankets, and thermally insulated PPE. The test stand will be made with fire-retardant materials.

Vacuum Chamber Vacuum testing requires modifications to a chamber in Caltech's Explosion Dynamics Laboratory. Dr. Joe Shepherd, head of the lab, will be consulted for a safety plan, with rigorous design reviews in collaboration with Caltech's EHS office. The vacuum chamber, built for detonation testing, exceeds our needs. For simulated flow, an N2 cold gas nozzle will be used for non-toxic testing.

Hazardous Materials Kevlar poses a potential safety risk at high temperatures, but testing will not reach temperatures causing toxic outgassing. Recommended PPE will be worn for unforeseen temperature spikes. Lunar regolith simulant hazards in the laboratory setting will be addressed with appropriate PPE, storage, and safety procedures.

3.11 Risk Assessment

	Negligible	Minor	Moderate	Severe
Frequent	MECH-02	ENV-02	MECH-03 MECH-04 MECH-09	
Likely		ENV-01	ENV-03 MECH-10 LOG-04	
Unlikely			MECH-06 MECH-11 LOG-01	MECH-07 LOG-02 LOG-03
Very Unlikely			ENV-05	MECH-05 OP-01 MECH-01

ID	Risk	Planned Mitigation/Testing
MECH-01	PILLARS does not inflate in a way that contains the regolith	CFD-04, CFDV-03, FT-03
MECH-02	Anchors cannot handle the stresses from the expanding plume's effect on PILLARS	MT-05
ENV-01	Craters formed from the repeated landings can cause uneven surfaces	Analysis of compatibility with low-SWaP surface preparation systems
MECH-03	PILLARS can deteriorate quickly due to the plume force and pressure	CFD-01, CFD-02, CFDV-03, MT-03
MECH-04	PILLARS can deteriorate quickly from the regolith abrasion	CFD-03, MT-01, MT-02, MT-03
MECH-05	PILLARS can become dislodged from its location	CFD-01, MT-05
MECH-06	PILLARS does not contain enough of the disturbed regolith	CFD-03, CFDV-02, FT-03
ENV-02	UV, Temperature, and regolith environment could weaken the Kevlar mesh	System Lifetime Material Analysis using DSNE data
MECH-07	PILLARS cannot unfold or deploy properly	FT-01
OP-01	PILLARS is unsafe for astronaut traversal	FT-02
MECH-08	Long term effects of factors such as rocket chemicals on system are unknown	System Lifetime Material Analysis and estimation

ID	Risk	Planned Mitigation/Testing
ENV-03	Accumulated regolith from previous launches is accelerated by plume and impacts rocket	CFD-03, CFDV-02
MECH-09	Initial thrust on take-off will eject some regolith before PILLARS can fully expand	CFD-03, CFD-04, CFDV-02, CFDV-03
MECH-10	Off-centered landing could cause failure shear on the anchors	CFD-01, CFD-02, MT-05
ENV-04	Anchors are dug out due to cratering	CFD-02
ENV-05	Regolith may build up in system that may result in undesired work to service system	CFD-02, CFDV-02. If regolith build up is significant, an automated cleaning system will be implemented.
MECH-11	Anchor and inflatable connection tears	MT-06
LOG-01	Incomplete test articles in timeline	Limit to core driving requirements/minimum viable testing
LOG-02	Human safety hazards with dust, vacuum, temperatures, etc.	Thorough safety planning with Caltech's office of Environmental Health and Safety
LOG-03	CFD Simulations result in unforeseen feasibility challenges	Early push for CFD analysis to determine if descoping/ redesigns are necessary
LOG-04	Unforeseen delays in simulations, fabrication, testing, etc.	Plan extra margin into scheduling

Figure 3-14: This is a risk matrix of key design and logistical issues.

3.12 Path to Flight and Infusion

Subsystem/ Component	Area of Concern	Modification
Dust Mitigation in Anchoring system	Earth-testing anchoring system will not be rated for lunar dust	Implement dust mitigation features like those on the Honeybee Robotics TRIDENT Drill
Full System Verification	All critical functionalities of the system are infeasible to test simultaneously	Propose a technology demonstration mission on a scaled down version of the system
Inflatable Deployment System	The Earth deployment mechanism is not rated for the space environment	Utilize existing, high TRL inflation systems.
System deployment	Robotic or astronaut based deployment	Develop low power systems and procedures to enable the deployment of the infrastructure
Landing Site Maintenance	Multiple landings may significantly change topography of landing site	Partner with power efficient systems for surface preparation
Inflatable Material	Large thermal swings, UV degradation, abrasion, etc. can decrease the lifespan of the system	Utilize the proposed flight materials for the inflatable
Inflatable Structure Lifetime	Dust build up and micrometeorites may decrease the performance of the system	Further analysis conducted on these parameters and mitigation steps taken
Payload Interface	There needs to be a mechanism to safely secure the various system components to a launch vehicle and a transportation vehicle	Develop an interface to attach to landers and transportation vehicles

Figure 3-15: This table shows changes the Earth demonstration system needed in order to be ready for flight.

At the end of the BIG Idea Challenge, we will have delivered critical verification of the key components of PILLARS in addition to simulations of the interactions between the plume, lunar surface, and inflatable berm. With this development, the system will be at TRL 5. Further development may be done NASA Game Changing Development (GCD) program under the "LAND" subset of GCD Projects [26] to develop our mid-trl system to TRL 6-7 by 2027.

The following 2 years will culminate in a 2029 technology demonstration mission through LFT-1 or CLPS initiatives to verify a scaled down PILLARS system in a lunar environment. A testing scheme with flight proven systems such as a CLPS lander, the Micro-Nova hopper [6], and the Stereo Cameras for Lunar Plume-Surface Studies (SCALPSS) imaging system [34] can be developed to simulate and analyze dust mitigation from a rocket launch and landing. Successful verification can lead to full system infusion into Artemis to support the establishment of large-scale ISRU infrastructure systems set to occur past 2030 [24].

4 Capabilities Statement

The Caltech Air and Outer Space (CAOS) organization at Caltech is a professional organization promoting innovation in engineering. With extensive team member and advisor experience, our team is poised to see similar successes as those before us. In 2021 and 2022, CAOS developed the HOMES and LATTICE systems, both of which were accepted as finalists in their respective BIG Idea challenges. Our team is fortunate to receive mentorship from students heavily involved in these projects, guiding our path towards similar successes.

Our team is split into three subteams: (1) Mechanical, (2) Materials, and (3) System Integration. The Mechanical subteam is responsible for fluid and structural analysis of our system and prototyping design. The Materials subteam is responsible for assessing the properties of materials used in our inflatable and fabrication methods. The System Integration subteam is focused on conceptual design and integration of information from the other two subteams in addition to developing and implementing a testing scheme. Our leadership team consists of seven undergraduates, with Lily Coffin as Systems Lead, Isabella Kwaterski as Materials Lead, James A. Scott III as Deployment Lead, and Samuel Foxman as Fluids Lead. In addition to these leads, Kevin Gauld is the Project Management Lead, and Emily Xu and Hannah Ramsperger are our Mission Concept co-leads. Communication among team members is facilitated through online communications as well as twice-weekly in-person work sessions.

The team schedule is based on the Agile method of project management. The development of PILLARS is guided by the Functional Requirements set in 4.1. The team meets once a week for a long (3-hour) work session, once a week for a short (1 hour) full team tag-up session led by the leadership team, and once a week for a short (1 hour) subteam tag-up led by the respective lead. Additional unofficial work sessions are organized throughout the week by the subteams along with individual work and research time. To ensure steady progress, one to four-week sprints are set. Demarcating the end of each sprint is a technical review. Leading up to the proposal, the team conducted a formal Preliminary Design Review and Mission Concept Review, from which we received valuable feedback from experts in various aerospace engineering design fields. If awarded funding, this structure of regular tag-ups, sprints, and technical reviews will continue. During the summer of 2024, six students will be awarded a Summer Undergraduate Research Fellowship, through which they will be able to contribute to the development of PILLARS as full-time employees of Caltech. We will also facilitate work done by four first-year students through the First Year Success Research Institute (FSRI) program fully funded by Caltech.

Crucial to our continued success, we have been able to enlist the support and advice from several renowned experts in the field of aeronautics and space engineering. Kalind Carpenter, a Robotics Mechanical Engineer at JPL, has been integral to the development of this project. His consistent presence in our weekly design reviews has not only provided us with invaluable feedback but also propelled our progress forward. Furthermore, his involvement in two Game Changing Development projects (COLDArm and CADRE) has provided us with crucial insights and connections with the forefront of lunar surface innovation. Additionally, we have had the fortunate opportunity to meet and discuss with Gregory Agnes, Group Supervisor for JPL's advanced robotic systems team, who provides the team with crucial advice to mission concept development and practical advice in subsystem design. We have also received continued support from our advisor, Dr. Charles Elachi. His experience as the former director of JPL for 16 years, Professor Emeritus in Electrical Engineering and Planetary Science at Caltech, and project lead for countless space science missions position him as an invaluable advisor to evaluate the scientific and engineering credibility of PILLARS.

To ensure that the team is accountable for its progress, we will be meeting with these advisors once a month or more as needed at the end of each sprint. Finally, Dr. Soon-Jo Chung, a Bren Professor of Aerospace and Jet Propulsion Laboratory Research Scientist, has played a critical role as our primary advisor. A cutting-edge researcher in the field of spacecraft systems and aerospace robotics, Dr. Chung continues to motivate the team to develop state-of-the-art technology while ensuring that the team runs smoothly. We will meet with Dr. Chung for weekly meetings. We will continue to receive guidance from these distinguished engineers and scientists if PILLARS is selected to compete in the BIG Idea Forum.

Figure 4-16: Images of Dr. Chung's lab workspace (top left), CAOS Lab (top right), Dr. Shepherd's vacuum chamber (bottom left) and Caltech's machine shop (bottom right).

We have also formed various partnerships to help develop PILLARS. One such partnership is with Cislune, a lunar construction and ISRU company. We aim to work with Cislune on developing a rocket test stand. We will also collaborate with VJ Technologies, a company focused on the development of industrial-scale X-ray computed tomography systems to image our material before and after testing to find any microscale defects within the inflatable layer. Finally, we have partnered with Dr. Joe Shepherd in the Caltech Explosion Dynamics Lab to access a thermal vacuum chamber for testing material properties for the inflatable. Dr. Shepherd is and has been an invaluable source of support for both facilities and expertise on the PILLARS project.

The PILLARS team has access to modern facilities to manufacture, assemble, and test PILLARS. Caltech Air and Outer Space manages a sub-basement laboratory at Caltech which will serve as the headquarters for the development of PILLARS. This lab accommodates all team members at once and is outfitted with workstations, 3D printers, hand tools, and electronic testing equipment. Additionally, the team has access to the Jim Hall Design and Prototyping Laboratory, outfitted with manual and CNC mills and lathes, waterjet machines, laser cutters, 3D printers, band saws, and more. This shop will be primarily used for quick turnaround parts for prototyping without tight tolerances. CAOS has a standing relationship with the GALCIT Machine Shop, an on-campus professional shop dedicated to precision machining. This shop will be used for tight tolerance machining operations in functional and final prototypes. In addition, the team is provided with 500 kilograms of the Colorado School of Mines Lunar Highland Type 1 (CSM-LHT-1) regolith simulant in the CAOS lab space to be able to carry out tests as realistically as possible on a smaller scale. Together, these facilities will allow the team to quickly develop and test PILLARS.

5 Diversity, Equity, Inclusion and Accessibility Statement

Our team firmly believes that diversity fosters innovation. By developing an equitable team environment that respects and promotes diverse voices, we can better challenge conventional thinking, encourage creative problem solving, and generate new ideas. To reinforce our commitment to nurturing a diverse and inclusive team, we have taken numerous actions.
Caltech's First-year Success Research Institute (FSRI) brings in incoming first-year students from historically underrepresented backgrounds and identities to provide them with a comprehensive orientation, mentorship, and research experience during their summer before starting at Caltech. CAOS takes in a number of FSRI students each summer and provides them with hands-on research projects and mentorship. On past Big Idea projects, FSRI students have played significant roles in project development during the summer, and have gone on to take on leadership roles within past Big Idea Projects and within CAOS. If awarded funding, FSRI students would have the chance to work on PILLARS over this upcoming summer, gaining valuable technical and research experience, as well as mentorship from fellow team members.

Additionally, PILLARS will be reaching out to local Minority Serving institutions such as Pasadena City College (PCC) to provide students with the opportunity to join the team. By reaching out to students outside of Caltech, we are capitalizing on the unique experience and expertise available in the local area of Pasadena.

Figure 5-17: CAOS FSRI students at a research poster presentation.

Furthermore, the PILLARS team hails from a vast diversity of technical disciplines, ethnicities, gender identities, and ages, to name a few. Within PILLARS, there is a place for anyone regardless of identity and background to contribute. We have demonstrated this capability in the past with the 2022 BIG Idea Challenge in which a total of 62 undergraduates (half of them being underrepresented minorities) made contributions to the project throughout the proposal, design, and verification phases of the project.

In addition to the inclusion of underrepresented minorities on the project, we will also conduct outreach to inspire the next generation. CAOS already hosts regular lab tours for underrepresented highschoolers and plans to collaborate with organizations such as the Caltech chapter of the Society of Hispanic Professional Engineers to present exciting projects such as PILLARS along with professional advice in hopes of inspiring and enabling more URMs to pursue a career in STEM.

Through these steps, we hope to promote the values of diversity, equity, and inclusion within the PILLARS project to work towards a more diverse and equitable community within Caltech and beyond.

6 Detailed Timeline

Until the first installment of funding, we will look into sourcing funding and software relevant to simulations we would like to conduct. Upon receiving the first installment, we will begin material acquisition and simulation. In partnership with Cislune, we will begin our first phase of fluid simulations. We will also begin acquiring berm materials for abrasion testing. In conjunction with this, we will design a rig for the first phase of vacuum testing. This will require materials to be sourced and machined in house. We will be ready for vacuum testing by early May 2024, with decisions hinging on simulations completing in late April 2024.

As we progress from our first stage of vacuum testing to dirty vacuum testing, we will have our first design review, allowing us to modify our final system based on the feedback of the audience, consisting of our advisors and members of the Caltech and Jet Propulsion Laboratory communities. This review will come just before the Mid Project Report. After this design review, we will finish our testing and CFD simulations with the assistance of students working full time over the summer through the Summer Undergraduate Research Fellowship. Also during this time, we will run sandblast tests to test the abrasion of the berm material under stresses. These sandblast tests will run for various lengths of time, allowing for lifetime-scale analysis of our material. By modifying the temperature within the sandblast chamber, we will also be able to assess the effect of temperature on material strength, informing our berm thickness decisions. We will utilize the Computed Tomography systems at VJ Technologies to image the berm, looking for defects at microscale both within and on the surface of the material.

In late June, we will receive the second installment of our stipend. At this time, we will pivot, looking to use a test stand developed jointly with Cislune. Having begun work on designing a 1/10 scale system earlier, we will finish our design and modify the test stand to allow us to run a hot fire test. The design of our scale system will be heavily based on the outcomes of our CFD simulations, as we will be nearing the end of our simulation development at this point of the project. This hot fire test will allow us to test inflation under the stress of the rocket plume after significant simulations of this event. Following this test, we will have a second design review in late August or early September, allowing us to complete our risk assessment and make modifications to our design, with a flight-ready prototype developed by the final report deadline in mid October.

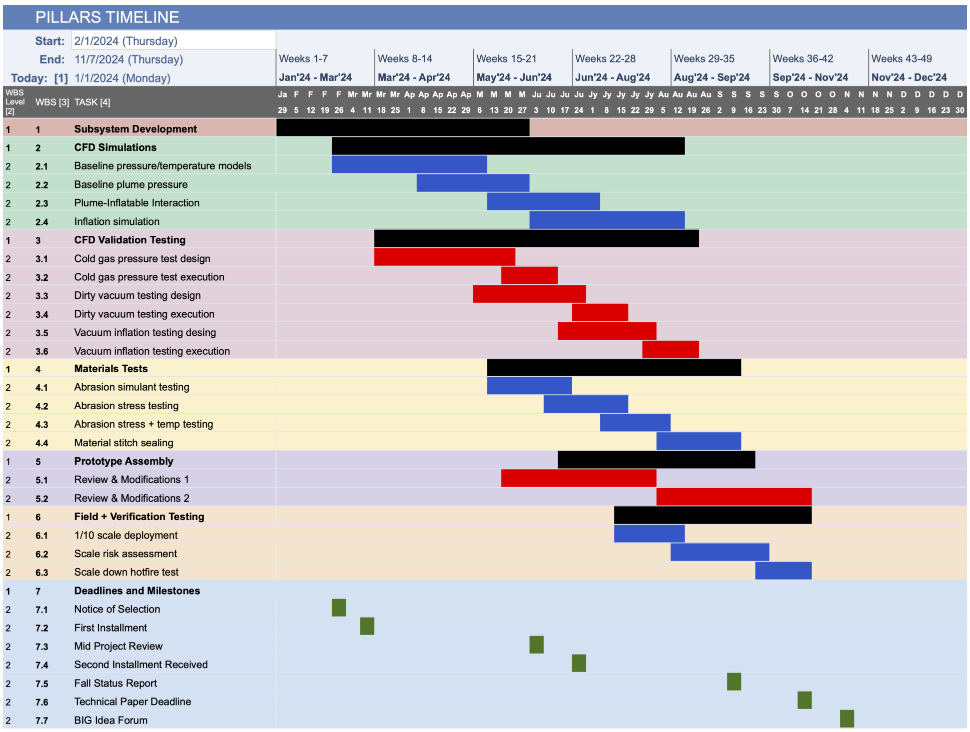


Figure 6-18: GANTT Chart of Project Timeline

7 Budget and Cost Notes

A. Direct Labor

- Key Personnel

Principal Investigator: Dr. Soon-Jo Chung will be responsible for the overall coordination of the project and the supervision of the undergraduate students and other project personnel. No salary is being requested for his effort. We will also be closely working with **Mr. Kalind Carpenter** affiliated with the NASA Jet Propulsion Laboratory.

- Other Personnel

Summer Undergraduate Research Fellowship (SURF) Program:
Six undergraduate students are anticipated to participate in Caltech's SURF program during the summer of 2024. These full-time positions are 10 weeks long, and are mentored by Dr. Soon-Jo Chung, our Faculty Advisor. These appointments will be fully dedicated to prototyping and testing PILLARS. Students will receive a stipend of $7,740 for the ten-week period. We are only requesting funds to support half of the stipend at $3,870 for each student, totaling $23,220. The SURF program is a cost-effective way of keeping the team on campus and fully involved in the project during the summer months.

First-year Success Research Institute (FSRI) Program:
Four first-year undergraduate students will join the PILLAR team as part of the FSRI program at Caltech. This program introduces incoming first-year students primarily from disadvantaged backgrounds to research at Caltech. This will allow us to capitalize on new personnel entering the program. As such, FSRI is an incredibly useful program for sourcing new students to work on PILLAR. No funds are being requested.

B. Fringe Benefits

None requested

C. Equipment

We will be using a thermal vacuum chamber in the Caltech Explosion Dynamics Laboratory under Dr. Joseph Shepherd. To facilitate this usage, we allocate $15,000 in Phase I (nothing in Phase II) to developing modifications to this vacuum chamber to suit the needs of PILLARS.

D. Domestic Travel

The travel costs of the budget consist of the expenses related to attending the 2024 BIG Idea Forum in NASA's Langley Research Center, Hampton, VA in November 2024. These estimates are based on the historical data of travel costs from Los Angeles, California to Hampton, VA. Travel costs are calculated for a total of 12 participants, which include the current undergraduate team and advisors Dr. Chung and Mr. Kalind Carpenter.

Cost Category	Rate	# of People	Total
Conference Registration	$500/person	12	$6,000.00
Airfare	$450/person (including baggage)	12	$5,400.00
Hotel Stay	6 people/room X 2 rooms X 4 nights	12	$1,218.00
Car Rental (SUV)	3 cars x 4 days + Gas	12	$1,380.00
Meals per diem	$59.00/day x 3 days $44.25/day x 2 days	12	$3,186.00
		Total:	$17,180.00

Figure 7-19: Table of Proposed Travel Expenses

If there is no in-person Forum, the travel funds will be re-aligned to use toward additional vacuum chamber tests, as well as labor hours spent over the summer to conduct the additional testing (extra SURF students, etc.). We will also conduct additional larger-scale testing on the Cislune rocket test stand if possible.

E. Other Direct Costs

- Materials and Supplies

The bill of materials consists of the costs associated with the purchase of the materials and components that will be needed to manufacture the prototypes and run tests. These materials include $40m^2$ of Aluminized Kapton Kevlar for testing and the construction of the outer inflatable layer, $21m^2$ of PTFE-Coated Kevlar for testing and the construction of the inner mesh layer, inflatable sealant to ensure the structural integrity of our down-scaled model, and 10 titanium stakes to be used for anchoring during plume testing of our model. The cost estimates of the different components and materials are through supplier websites and quotes provided by suppliers such as Dunmore, AFC Materials, and Mc-Master-Carr.

Item	Description	Phase I	Phase II	Total
Aluminized kapton kevlar	20 m^2 for inflatable layer 20 m^2 for testing	$24,000	$0	$24,000
PTFE coated Kevlar	13 m^2 for mesh layer 8 m^2 for testing	$8,000	$400	$8,400
Titanium Stakes	10 stakes for earth-demo anchoring	$0	$3,000	$3,000
Sealant	Sealant for inflatable structure	$0	$1,000	$1,000
	Total:	$32,000	$4,400	$36,400

Figure 7-20: Table of Proposed Materials Expenses

- Testing Costs or Facilities Rentals

The testing costs serve to ensure we are able to verify and validate the design of PILLARS. We aim to machine as much as possible on campus, utilizing the Jim Hall prototyping shop and GALCIT machine shop for machine time. We will partner with companies to facilitate much of our testing. For a test stand, we are partnering with Cislune for access to a test stand being developed, given we produce our own parts to fit PILLARS onto the test stand and complete some of the system design. We will also partner with VJ Technologies, giving us access to X-Ray systems to conduct Computed Tomography scans of our inflatable after abrasion. This imaging either requires significant travel or shipping costs, so we allocate budget in Phase II for these costs. We will also use 3D printers within our campus lab space, which is funded by our overarching Caltech Air and Outer Space student organization.

Item	Description	Phase I	Phase II	Total
Machine Shop Rental	~100 hours of use in the GALCIT machine shop	$6,000	$0	$6,000
	~200 hours of use in the Jim Hall machine shop split between Phase I & II	$1,500	$500	$2,000
X-Ray Testing	Cost of shipping to New York for CT scans of our materials in partnership with VJ Technologies	$0	$1,500	$1,500
Rocket Test Stand	Materials, and consumables for a rocket test stand developed in partnership with Cislune	$5,500	$2,000	$8,000
PPE	PPE for testing- i.e. respirators, etc.	$0	$1,500	$1,500
	Total:	$13,000	$5,500	$18,500

Figure 7-21: Table of Proposed Facilities Expenses

F. Indirect Costs

Phase	Institution	Rate	Cost
I	California Institute of Technology	25% on direct costs	$15,000
II	California Institute of Technology	25% on direct costs	$12,575
	California Space Grant Consortium	48.5% on first $25K of direct costs	$12,125
		Total Indirect Cost	$39,700

Figure 7-22: Table of Proposed Indirect Costs

California Institute of Technology: The indirect cost is calculated at 25% of total direct costs (or 20% of total cost). The reduced indirect cost rate of 25% total direct costs is applied by special approval from the Caltech Provost.

California Space Grant Consortium / University of California, San Diego The indirect cost is calculated at 48.5% of total modified direct costs, which only includes the first $25,000 of the subaward that will be issued to the California Institute of Technology.

Caltech
PILLARS: Plume-deployed Inflatable for Launch and Landing Abrasive Regolith Shielding
2024 BIG Idea Challenge

Budget Period of Performance: February 1 - December 31, 2024

*****Please leave formulas in the clickable cells*****

Description	Rate / #	Phase 1 2/1/24 - 6/30/24	Rate	Phase 2 7/1/24 - 12/31/24	Total
A. Direct Labor - Key Personnel					
Dr. Soon-Jo Chung's Salary (Waived)		$ -		$ -	$ -
Subtotal Salary		***$ -***		***$ -***	***$ -***
Direct Labor - Other Personnel					
SURF Labor Costs (6 UGs, 50% covered by Caltech)		$ -		$ 23,220.00	$ 23,220.00
FSRI Research Fellowship (4 UGs, Fully covered by Caltech)		$ -		$ -	$ -
Subtotal Other Personnel		***$ -***		***$ 23,220.00***	***$ 23,220.00***
B. Fringe Benefits					
Students	0%	$ -	0%	$ -	$ -
					$ -
Subtotal Fringe		***$ -***		***$ -***	***$ -***
Total Labor Costs (A+B)		**$ -**		**$ 23,220.00**	**$ 23,220.00**
C. Direct Costs - Equipment (any individual item over $5,000)		**$ 15,000.00**			**$ 15,000.00**
D. Direct Costs - Domestic Travel		**$ -**		**$ 17,180.00**	**$ 17,180.00**
E. Other Direct Costs					
Materials and Supplies		$ 32,000.00		$ 4,400.00	$ 36,400.00
Testing Costs or Facilities Rental		$ 13,000.00		$ 5,500.00	$ 18,500.00
Consultants		$ -		$ -	$ -
Services		$ -		$ -	$ -
Subcontracts/Subawards		$ -		$ -	$ -
Miscellaneous		$ -		$ -	$ -
Total Other Direct Costs (E)		***$ 45,000.00***		***$ 9,900.00***	***$ 54,900.00***
F. Total Direct Costs (A+B+C+D+E)		**$ 60,000.00**		**$ 50,300.00**	**$ 110,300.00**
Modified Total Direct Costs, if applicable		$ 60,000.00		$ 50,300.00	$ 110,300.00
G.i. University Indirect Costs (Phase I & Phase II)	25%	$ 15,000.00	25%	$ 12,575.00	$ 27,575.00
G.ii. Space Grant Indirect Costs (Phase II only, if applicable)			48.5% on 25K	$ 12,125.00	$ 12,125.00
G. Total Indirect Costs		**$ 15,000.00**		**$ 24,700.00**	**$ 39,700.00**
H. Total Direct and Indirect Costs (F+G)		**$ 75,000.00**		**$ 75,000.00**	**$150,000.00**
% of Total Budget (Phase I should be 50%; Phase II should be 50%)		***50.00%***		***50.00%***	

References

[1] *A Lunar/Martian Anchor Emplacement System*. NASA-CS-197193. University of Idaho, Moscow, Idaho, 1995. URL: https://ntrs.nasa.gov/api/citations/19950006277/downloads/19950006277.pdf.

[2] *Adhesive Compounds for Bonding Kevlar Substrates*. URL: https://www.masterbond.com/applications/adhesive-compounds-bonding-kevlar-substrates.

[3] *Astrobotic Demo Mission*. 2023. URL: https://www.astrobotic.com/astrobotic-wins-34-6m-for-power-demo-mission-on-the-moon/.

[4] Kaila Coimbra et al. "Design of a Lunar Architecture for Tree Traversal in Service of Cabled Exploration". In: *AIAA SCITECH 2023 Forum*. American Institute of Aeronautics and Astronautics, 2023, Art. No. 2023–0020. ISBN: 978-1-62410-699-6.

[5] Jason Crabtree et al. "Helical Anchors: Lateral Resistance for Shaping the Lunar Surface". In: *Earth & Space 2008*, pp. 1–10. DOI: 10.1061/40988(323)118. eprint: https://ascelibrary.org/doi/pdf/10.1061/40988%28323%29118. URL: https://ascelibrary.org/doi/abs/10.1061/40988%28323%29118.

[6] T.P. Crain et al. "S. P. Hopper: First In-Situ Exploration of Lunar Polar Terrain". In: Jan. 2022.

[7] Bob Esser et al. *The Path to an Enduring Lunar Presence*. 2023. URL: https://lsic.jhuapl.edu/Resources/files/The%20Path%20to%20an%20Enduring%20Lunar%20Presence.pdf.

[8] Douglas Fontes, James G. Mantovani, and Philip Metzger. "Numerical estimations of lunar regolith trajectories and damage potential due to rocket plumes". In: *Acta Astronautica* 195 (2022), pp. 169–182. ISSN: 0094-5765. DOI: https://doi.org/10.1016/j.actaastro.2022.02.016. URL: https://www.sciencedirect.com/science/article/pii/S0094576522000716.

[9] Matthew Heverly and Jaret Matthews. "A Wheel-on-limb rover for lunar operation". In: (Jan. 2008).

[10] *Horn Torus*. URL: https://mathworld.wolfram.com/HornTorus.html.

[11] Christopher Immer, John Lane, and Philip Metzger. "Moon safe for long-term human exploration, first surface radiation measurements show". In: *Science* (2020). URL: https://www.science.org/content/article/moon-safe-long-term-human-exploration-first-surface-radiation-measurements-show.

[12] Christopher Immer et al. "Apollo 12 Lunar Module exhaust plume impingement on Lunar Surveyor III". In: *Icarus* 211.2 (2011), pp. 1089–1102. ISSN: 0019-1035. DOI: https://doi.org/10.1016/j.icarus.2010.11.013. URL: https://www.sciencedirect.com/science/article/pii/S001910351000432X.

[13] Christopher Immer et al. "Apollo video photogrammetry estimation of plume impingement effects". In: *Icarus* 214.1 (2011), pp. 46–52. ISSN: 0019-1035. DOI: https://doi.org/10.1016/j.icarus.2011.04.018. URL: https://www.sciencedirect.com/science/article/pii/S0019103511001539.

[14] Matthew Kuhns et al. "Deep Regolith Cratering and Plume Effects Modeling for Lunar Landing Sites". In: *Earth and Space 2021*, pp. 62–78. DOI: 10.1061/9780784483374.007. eprint: https://ascelibrary.org/doi/pdf/10.1061/9780784483374.007. URL: https://ascelibrary.org/doi/abs/10.1061/9780784483374.007.

[15] Matthew Kuhns et al. "Instant Landing Pads for Lunar Missions". In: *Earth and Space 2021*, pp. 1027–1032. DOI: 10.1061/9780784483374.094. eprint: https://ascelibrary.org/doi/pdf/10.1061/9780784483374.094. URL: https://ascelibrary.org/doi/abs/10.1061/9780784483374.094.

[16] John E. Lane and Philip T. Metzger. "Estimation of Apollo Lunar Dust Transport using Optical Extinction Measurements". In: *Acta Geophysica* 63.2 (2015), pp. 568–599. ISSN: 1895-7455. DOI: 10.1515/acgeo-2015-0005. URL: https://doi.org/10.1515/acgeo-2015-0005.

[17] *Manta Ray Soil Anchor*. URL: https://www.williamsform.com/soil/manta-ray-anchors/.

[18] Philip T. Metzger and Greg W. Autry. "The Cost of Lunar Landing Pads with a Trade Study of Construction Methods". In: *New Space* 11.2 (2023), pp. 94–123. DOI: 10.1089/space.2022.0015. eprint: https://doi.org/10.1089/space.2022.0015. URL: https://doi.org/10.1089/space.2022.0015.

[19] Philip T. Metzger, Jacob Smith, and John E. Lane. "Phenomenology of soil erosion due to rocket exhaust on the Moon and the Mauna Kea lunar test site". In: *Journal of Geophysical Research: Planets* 116.E6 (2011). DOI: https://doi.org/10.1029/2010JE003745. eprint: https://agupubs.onlinelibrary.wiley.com/doi/pdf/10.1029/2010JE003745. URL: https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2010JE003745.

[20] Aaron Benjamin Morris. PhD thesis. University of Texas, 2012.

[21] Rongjun Mu et al. "A Distributed Radio Beacon/IMU/Altimeter Integrated Localization Scheme with Uncertain Initial Beacon Locations for Lunar Pinpoint Landing". In: *Sensors* 20.19 (2020). ISSN: 1424-8220. DOI: 10.3390/s20195643. URL: https://www.mdpi.com/1424-8220/20/19/5643.

[22] Robert Mueller. *Lunar Landing Launch Pads*. NASALSIC Excavation Construction Focus Group. Swamp Works, NASA KSC, 2020. URL: https://lsic.jhuapl.edu/uploadedDocs/focus-files/615-E&C%202020%2010%20-%20Lunar%20Landing%20&%20Launchpads,%20Rob%20Mueller.pdf.

[23] NASA. *BIG Idea Challenge 2024 Proposal Guidelines*. 2023. URL: https://bigidea.nianet.org/wp-content/uploads/2024-BIG-Idea-Challenge-Proposal-Guidelines.pdf.

[24] NASA. *FY 2024 PRESIDENT'S BUDGET REQUEST*. 2023. URL: https://www.nasa.gov/wp-content/uploads/2023/03/nasa-fy-2024-cj-v3.pdf.

[25] NASA. *NASA Moon to Mars Architecture Definition Document*. NASA/TP-20230017458. Washington, DC, USA, 2024. URL: https://www.nasa.gov/wp-content/uploads/2024/01/rev-a-acr23-esdmd-001-m2madd.pdf?emrc=65bc346d13714.

[26] *NASA Game Changing Development Projects*. 2024. URL: https://www.nasa.gov/game-changing-development-projects/.

[27] *NASA Lunar Surface Innovation Initiative*. 2024. URL: https://www.nasa.gov/space-technology-mission-directorate/lunar-surface-innovation-initiative/.

[28] Michael Pohlen et al. "Overview of lunar dust toxicity risk". In: *npj Microgravity* 8.1 (2022), p. 55. ISSN: 2373-8065. DOI: 10.1038/s41526-022-00244-1. URL: https://doi.org/10.1038/s41526-022-00244-1.

[29] Amia K. Ross et al. "Preliminary quantification of the available solar power near the lunar South Pole". In: *Acta Astronautica* 211 (2023), pp. 616–630. ISSN: 0094-5765. DOI: https://doi.org/10.1016/j.actaastro.2023.06.040. URL: https://www.sciencedirect.com/science/article/pii/S0094576523003399.

[30] Sakai Shin-ichiro. *Smart Lander for Investigating Moon (SLIM) Results from the Moon Landing*. 2024. URL: https://www.isas.jaxa.jp/en/outreach/announcements/files/SLIM-pressconf-20240125.pdf.

[31] *SpaceX Starship*. URL: https://www.spacex.com/vehicles/starship/.

[32] Paul J. van Susante and Philip T. Metzger. "Design, Test, and Simulation of Lunar and Mars Landing Pad Soil Stabilization Built with In Situ Rock Utilization". In: *Earth and Space 2016*, pp. 642–652. DOI: 10.1061/9780784479971.060. eprint: https://ascelibrary.org/doi/pdf/10.1061/9780784479971.060. URL: https://ascelibrary.org/doi/abs/10.1061/9780784479971.060.

[33] Paul J. van Susante and Philip T. Metzger. "Design, Test, and Simulation of Lunar and Mars Landing Pad Soil Stabilization Built with In Situ Rock Utilization". In: *Earth and Space 2016*, pp. 642–652. DOI: 10.1061/9780784479971.060. eprint: https://ascelibrary.org/doi/pdf/10.1061/9780784479971.060. URL: https://ascelibrary.org/doi/abs/10.1061/9780784479971.060.

[34] Ryan Thompson et al. "Stereo Camera Simulation for Lunar Surface Photogrammetry". In: Jan. 2021. DOI: 10.2514/6.2021-0358.

[35] TRAVIS VAZANSKY et al. *LUNAR IN-SITU LANDING/LAUNCH ENVIRONMENT (LILL-E) PAD*. 2021. URL: https://bigidea.nianet.org/wp-content/uploads/Colorado-School-of-Mines-Final-Technical-Paper-2021-BIG-Idea.pdf.

[36] Mark Wade. URL: https://web.archive.org/web/20021117170847/http://www.astronautix.com/craft/lmalsion.htm.

[37] David W. Way et al. "Assessment of the Mars 2020 Entry, Descent, and Landing Simulation". In: *AIAA SCITECH 2022 Forum*. DOI: 10.2514/6.2022-0421. eprint: https://arc.aiaa.org/doi/pdf/10.2514/6.2022-0421. URL: https://arc.aiaa.org/doi/abs/10.2514/6.2022-0421.

[38] Hongwei Yang, Ruihong Yang, and Qian Wang. "Laboratory construction and curation scheme for returned samples of the chang'e-5 mission". In: *Geoscience Letters* 9.1 (2022), p. 19. ISSN: 2196-4092. DOI: 10.1186/s40562-022-00224-z. URL: https://doi.org/10.1186/s40562-022-00224-z.

[39] Qing Ye et al. "Numerical Simulation of Flows Field Characteristics of High Altitude Liquid Rocket Exhaust Plume". In: *IOP Conference Series: Materials Science and Engineering* 711.1 (2020), p. 012110. DOI: 10.1088/1757-899X/711/1/012110. URL: https://dx.doi.org/10.1088/1757-899X/711/1/012110.

[40] Kris Zacny et al. "TRIDENT Drill for VIPER and PRIME-1 Missions to the Moon". In: Jan. 2023, pp. 465–474. DOI: 10.1061/9780784484470.043.